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A Guide to Thermal Analysis and Testing

Chris Fry
AMEC

ABSTRACT

The Transport Container Standardisation Committee (TCSC) is a UK nuclear industry group whose main function is to examine the requirements for the safe transport of radioactive material with a view to standardisation and, as appropriate, produce and maintain guidance documentation. The Code of Practice "Thermal Analysis and Testing of Transport Package", TCSC 1093, was published in March 2012 following an extensive review lead by SERCO (now AMEC), peer review and approval by the TCSC committee.

Thermal performance is an important aspect of the design of any transport package and a key feature in regulatory testing and approval. The code of practice provides guidance on the thermal testing and analysis of packages, to supplement and support the information provided in the IAEA Regulations and the accompanying advisory material. It is intended to assist packaging designers in selecting their approach to thermal testing, as well as experimentalists performing thermal tests, and analysts modelling the thermal performance of transport packages. It describes what is required from a thermal assessment and the issues which should be considered. It also provides guidance on which method (i.e. testing or analysis) might be most appropriate for different types of package.

This paper provides an overview to the content of the guide to the thermal analysis and testing of transport packages, and includes topics such as:

- How to choose whether to perform practical tests or just numerical analysis
- Good practice when performing practical tests for normal conditions of transport
- Good practice when performing practical tests for accident conditions of transport (the fire test)
- Whether to use a CFD code or FE code for analysis and the selection of a suitable computer code
- Advice on the specification of material properties
- Advice on the application of boundary conditions
- Advice on modelling normal conditions of transport
- Advice on modelling accident conditions of transport
- Advice on whether models should be best estimate or pessimistic

INTRODUCTION

The Transport Container Standardisation Committee (TCSC) is a UK nuclear industry group whose main function is to examine the requirements for the safe transport of radioactive material with a view to standardisation and, as appropriate, produce and maintain guidance documentation.

Thermal performance is an important aspect of the design of any transport package and a key feature in regulatory testing and approval. The Transport Container Standardisation Committee has recently issued a good practice guide on thermal testing and modelling of transport packages (TCSC, 2012). This guide provides guidance on the thermal testing and analysis of packages, to supplement and support the information provided in the IAEA Regulations (IAEA, 2012) and the accompanying advisory material (IAEA, 2008). It is intended to assist packaging designers in selecting their approach to thermal testing, as well as experimentalists performing thermal tests, and analysts modelling the thermal performance of transport packages. It describes what is required from a thermal assessment and the issues which should be considered. It also provides guidance on which method (i.e. testing or analysis) might be most appropriate for different types of package.

The following sections of this paper contain extracts from the guide. The complete guide can be obtained from the TCSC through its website: www.tcsc.org.uk.

GUIDE INTRODUCTION

The IAEA Regulations (IAEA, 2012) require that temperatures of the packaging and contents be considered under both normal and accident conditions of transport, according to the package type. For Types B(U), B(M) and C packages, and for some packages containing fissile material, there are more demanding requirements for normal conditions of transport. These include the package surface temperature and the effects of heat build-up on the package integrity and internal pressure. The IAEA Regulations specify both the range of ambient temperatures and the heat flux from solar insolation that must be considered.

Additionally for Types B(U), B(M) and C packages etc., there are demanding thermal test requirements to verify the safety of the package contents under accident conditions of transport, comprising severe impact (or drop) tests followed by a fully engulfing fire.

The thermal assessment of a transport package is often inter-related with other aspects of the assessment:

- The temperatures experienced under both normal and accident conditions may cause thermal expansion leading to stresses and deformations in the package components.
- The temperatures experienced by the package under normal and accident conditions may need to be taken into consideration when deriving the properties of materials during the structural, impact or shielding assessment.
- The damage caused to the container during the drop tests will need to be taken into consideration when assessing the temperatures experienced during a fire test.
- Any loss of material (e.g. due to burning or melting) which occurs during the fire test will need to be taken into consideration when assessing the shielding.

This good practice guide is one of a series issued by TCSC. In using this guide, the reader is referred also to TCSC 1086 and TCSC 1087, which provide further guidance on drop testing of packages and on finite element analysis respectively.

TESTING OR ANALYSIS ?

It is possible for the thermal assessment of some packages to be performed by numerical analysis alone. For the majority of packages, however, the thermal assessment will include some practical tests. The decision on what practical tests should be performed will depend largely upon the design of the container. The Advisory Material (IAEA, 2008) associated with the IAEA Regulations, provides extensive advice on the conduct of practical and analytical thermal testing.

It should be noted that a practical test of temperatures during normal transport is not destructive. Therefore, if a full scale package is being built, either for testing under accident conditions or as a prototype, the additional expense involved in performing a thermal, normal transport test is probably quite modest. The performance of a test of temperatures under normal conditions of transport is recommended unless:

- The package design is such that heat transfer can be modelled with reasonable accuracy without any test data, or
- The safety margins are sufficiently large that pessimistic assumptions can be made to cover all uncertainties in the modelling, or
- Test data are already available from a very similar design of package.

A practical fire test is destructive in that, once exposed to a fire (or equivalent environment), the resulting thermal distortion, and any burning or melting, render the package unsuitable for any further purpose. A practical fire test can also only be performed at full scale since, from the equations describing heat conduction, scale model testing would only be applicable if the thermal properties of the materials from which the package is constructed could also be scaled (which is not feasible). It therefore follows that, if a practical fire test is to be performed on a complete package, a full-scale prototype of the package will need to be provided.

If a package design contains a natural material with a complex behaviour, such as wood, but it is not feasible to perform a practical thermal test on the complete package (for example due to the cost of manufacturing a full-scale prototype package and impact testing it prior to the thermal test), then separate effects tests on samples of the materials, under the expected conditions, should be considered. Thus, if it is only the behaviour of the wood inside the impact limiter of a package which is uncertain, a thermal test on just the impact limiter should be considered. Or if foam or seals need to be shown to be capable of withstanding temperatures above their stated upper temperature limit for a few hours, a separate test could be performed just to demonstrate this. Again, such separate effects tests should ideally be performed at full scale. Thus, to demonstrate the heat transfer across a layer of cork under thermal test conditions, a sample of similar thickness should be tested under the conditions expected in the thermal test. When designing such separate effects tests, careful consideration should be given to how they will be analysed and how to appropriately represent any effects resulting from adjacent structures which would be present in a thermal test on a complete package (e.g. the presence of the package inside the impact limiters).

The objective of any separate effects tests on materials with complex behaviour, such as wood, would be to validate, or demonstrate as pessimistic, the way that the material is represented in the numerical model. It should be noted that standard tests (e.g. British Standard tests) may not always be appropriate for the intended purpose. For example, the measurement of thermal conductivity of an insulating material (such as wood) may specify that the sample should first be dried, whereas, in a package, the drying process (and condensation of the steam generated) is an integral part of its thermal behaviour.

TESTING FOR NORMAL CONDITIONS OF TRANSPORT

Objective of Testing under Normal Conditions of Transport

The objective of a normal conditions of transport thermal test is to determine, for a known ambient temperature and internal heat load, the temperatures of the components of the packaging and contents. This enables the temperatures of the accessible surfaces to be determined and the performance of the package under the required mechanical test conditions to be evaluated.

Photo courtesy of Croft

Heating test on Safkeg 2816G

Set-up and Siting of Test Package

In a thermal test for normal conditions of transport, a full-scale package will usually be placed in a location where the ambient temperature can be controlled and electric heaters placed inside the package to simulate the heat generated by the radioactive material. The package will be left for sufficient time to reach steady conditions and its temperature measured.

The package should be located in a room which is sufficiently large to have a minimal effect upon the convective natural heat loss from the outer surface of the package. Thus the amount of free space required around the package will depend upon the magnitude of the heat flux from the package. The room where the test is conducted should, as far as possible, maintain a constant temperature naturally and should be free of any draughts, forced air flows or sunshine.

It should be noted that, in general, the objective of the test is to provide data that can be used to validate the numerical model. Thus having a uniform ambient temperature is more important than maintaining a specific temperature. For example, trying to create an ambient temperature of 38°C would probably require additional heaters which would create air currents (and possibly thermal stratification) which may affect the convective heat transfer from the package itself. If heaters (under thermostatic control) are provided in order to keep the ambient temperature constant, the target temperature should be as low as possible so that the heat required from the heaters is kept to a minimum.

The package, in its support cradle or transport frame if used, should be stood on a layer of insulating material on the floor of the room. The insulation of the package from the floor both provides pessimism and simplifies the comparison of the test data with the numerical model, since there may otherwise be considerable uncertainty in the heat being transferred to the floor, especially if its temperature is not being measured.

Normal transport thermal tests should be performed with a heat load as near the design maximum as practicable to best differentiate the performance from thermal "noise" such as variations in ambient temperature. Tests may be performed for different orientations of the package as appropriate to transport practice.

The inclusion of solar insolation during testing for Normal Conditions of Transport is generally not practical, since producing a solar insolation flux, at the same wavelength as that from the sun, at the level specified by the IAEA Regulations (which varies depending upon the orientation of the surface) would be very challenging to achieve. Thus performing a steady state test and then including the effect of solar insolation through analysis is the approach normally adopted.

Temperature Measurement

The package temperature is usually measured using thermocouples with an accuracy of ~1°C. In addition, a temperature probe can be used to measure the temperature of the accessible external surface. When mounting thermocouples, they should be placed, if at all possible, in good thermal contact with solid structures.

TESTING FOR ACCIDENT CONDITIONS OF TRANSPORT

Objective of Testing under Accident Conditions of Transport

The fire test is performed in order to demonstrate that a package can withstand an accidental fire as required by the IAEA Regulations, which require the thermal test to provide a heat flux all around the package at least equivalent to an average temperature of 800°C with a flame emissivity coefficient of 0.9.

Factors Influencing the Test Method

A pool fire simulates most closely the thermal environment to which the package might be subjected in an actual accident, but pool fire tests produce large plumes of soot, unburnt hydrocarbons and carbon dioxide. Thus, on environmental grounds, furnace tests are often preferred. Ovens or furnaces suitable for testing small packages are readily available but large furnace facilities are less easily procured.

Pool fire test of wooden shock absorber

Pool Fire Tests

For a pool fire test, the IAEA Advisory Material advises that the pool should extend between 1 and 3 m beyond the edges of the package to help ensure a fully engulfing severe fire. In practice, however, there is no control over the resulting flame temperature or emissivity coefficient. The temperature of the flames should, however, be measured on each side of the package and the competent authority may only judge the test as starting once the flame temperature has reached 800°C. In a pool fire it can be challenging to ensure that the flames engulf the entire package. Any wind, in particular, will tend to distort the flame cover. The use of flame guides (thin vertical panels) below the package is recommended as these have negligible effect upon the flame temperature but prevent the flames from blowing under the package and leaving the upwind side with little, or no, flame cover.

Furnace Tests

The temperature of a furnace is more controllable than that of a pool fire. In principle, therefore, a temperature close to (or ideally just in excess of) the 800°C specified in the IAEA Regulations should be achievable. The furnace may be pre-heated to the required temperature, but the act of opening the furnace for loading and the thermal mass of the package to be tested may reduce the temperature of the furnace considerably. The use of a relatively large and high power furnace, together with preheating to a higher temperature and ensuring a rapid loading procedure can minimize the cooling effect.

Photo courtesy of Croft

Furnace test of GB2802B

Temperature Measurements

Ideally, in either a pool fire or a furnace test, the transient temperature at important locations (e.g. the lid seals) would be measured using thermocouples. However, because the thermal test is conducted after the package has first been subjected to a series of drop tests, in practice it is virtually impossible to attach any thermocouples to the internals of the package as these would get damaged by, or interfere with, the drop tests. Thus, thermocouples are only attached to locations which are readily accessible just prior to the thermal test. Temperature sensitive strips, which record through colour change the maximum temperature experienced (within a range of a few degrees), are well suited to measuring the maximum temperature reached inside the package. These strips can be attached to various solid structures when the package is assembled and can readily withstand the acceleration forces during the drop tests.

In a pool fire, and probably also in a furnace, the temperature measurements made by thermocouples can be affected by the heat from the flames. This has been clearly observed in type K thermocouples of 1mm diameter or less. Larger diameter thermocouples are less affected by the flames. If the thermocouple tails are long, false junctions are formed which add a variable component of the flame temperature to the temperature being measured at the thermocouple tip. This effect does not damage the thermocouple and the interference stops as soon as the fire is extinguished. If the thermal test is performed on a test section or component rather than a complete package (as discussed above) then, because the test section or component will not have to be subjected to actual drop tests, the use of thermocouples to measure internal temperatures can be more readily accomplished.

THERMAL ANALYSIS TECHNIQUES

General Considerations

Where temperatures are to be determined by calculation, straightforward situations may be assessed by basic calculation methods. However, for the complex thermal conditions obtained in transport situations, particularly under fire accident conditions, computer-based techniques will be required. Both Computational Fluid Dynamics (CFD) and Finite

Element Analysis (FEA) codes can be used, in general, to solve thermal problems. Actually, the terms CFD and FEA are not mutually exclusive since some CFD codes use the finite element method. In general, however, most commercial CFD codes such as Fluent or CFX use a finite volume method and so are not classed as FEA codes.

CFD versus FEA

CFD codes are better suited than FEA codes for modelling convective heat transfer in complex or novel geometries. In the field of transport package heat transfer, a CFD code is more appropriate if a fluid medium (such as water) is used to transport heat around the interior of the package by natural convection (e.g. in some used fuel packages). CFD is also more appropriate for modelling heat transfer by convection and radiation from complex geometries on the exterior of a package (e.g. a finned surface covered by a shroud). Even if an FEA code is used to model the complete package, CFD may still be used to study particular aspects (such as heat transfer from a fin geometry on the outer surface).

Irrespective of whether a CFD or FEA code is used to perform the thermal analysis, the validation of the code needs to be demonstrated for the proposed application. Most FEA and CFD codes will be provided with validation cases. For CFD codes, however, these will probably focus more on modelling fluid flow than on conduction heat transfer. In 1986 a set of benchmark problems was established by NEACRP for demonstrating the ability of codes to accurately model transport package heat transfer problems (Glass, 1988). These relatively simple benchmark problems would still be appropriate as a basis for demonstrating the validation, for performing package heat transfer modelling, of any FEA or CFD code for which insufficient validation is considered currently to exist.

MODELLING – DESIGN OF THE MODEL

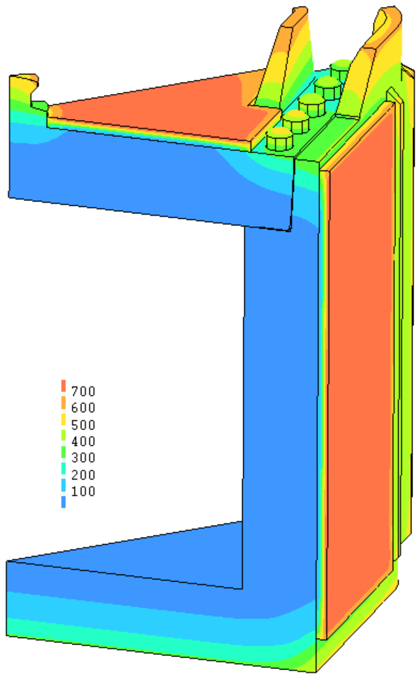
Simplification and Symmetry

It is worthwhile to simplify the model, if possible, in order to reduce the time required to perform the calculations. To this end, it may be possible to take advantage of design symmetry to model, say, a sector or quadrant of the design, or to consider a 2-dimensional model.

The Significance of Design Features

When designing a model and deciding the acceptable degree of simplification, it is important to assess the significance of the features of the design   To make these decisions, the analyst needs to consider the important outputs from the model (e.g. the temperature at the lid seals) and the important heat transfer paths which will affect these outputs.

For items which may not be a significant heat transfer path but are important in their own right (e.g. vent valves) it may be more appropriate not to include them in the model of the overall package but, instead, to represent them in detail in a separate model. This would enable the item to be modelled in appropriate detail without adding significant complication to the overall model. If appropriate, the separate model could be used to derive effective thermal properties (e.g. conductivity) which could be used in the overall model to represent the separate item in a simple way.



Temperature at end of fire predicted using FE model of SWTC-285 with vent valve omitted

Modelling Impact Damage

A consideration when deciding whether a 2-dimensional model is appropriate is the detail of impact damage that needs to represented in the model (since the fire test is performed on a package which has already been subjected to a series of drop tests). Drop tests are frequently performed onto corners and even a ‘slap down’ impact on an axi-symmetric package will produce damage which is not axi-symmetric.

MATERIAL PROPERTIES AND BOUNDARY CONDITIONS

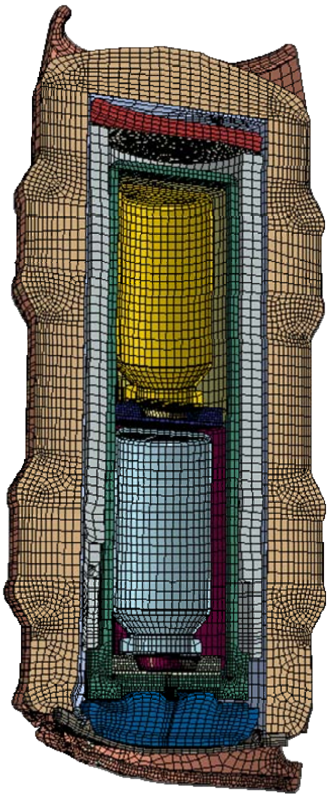
The Behaviour of Complex Materials

During the thermal (fire) test, some materials may be taken outside their normal range of operating temperatures (e.g. heating of foam to 800°C). Under these conditions, not only will material properties not generally be available but consideration will also have to be given to the behaviour of the material (e.g. charring). In particular this will apply to materials such as wood and cork which are commonly used in transport packages, or their shock absorbers, because of their ability to both provide insulation from a fire and absorb energy in drop tests. A further complication in the case of wood and cork is that they release steam and oils when they are heated which then condense on cool surfaces, introducing an additional heat transfer mechanism.

To ensure that the complex behaviour of materials such as foam, wood and cork at high temperature has been adequately captured in the thermal model, appropriate test data will be needed. It should be noted that standard tests (e.g. British Standard) may not always be appropriate and tests should be conducted, as far as possible, to reproduce the conditions the material will experience inside the transport package when exposed to the thermal (fire) test.

A separate effect test on a sample of material (of the correct thickness) has the advantage of being easier to analyse, since it will be designed to have just one dominating heat transfer path (through the material of interest). The results from a pool fire or furnace test on an actual prototype package, if performed, could alternatively be used to determine the effective thermal properties of any foam, wood or cork inside it. This has the advantage of reproducing most closely the correct thermal conditions but derivation of the thermal properties may be complicated by there being several important heat transfer paths and maybe more than one material whose properties are uncertain.

A further complication for wood is that, under some conditions, it will burn, potentially releasing heat for many hours after the pool fire has been extinguished or the package has been removed from the furnace. If the wood is clad in steel, this will prevent air from reaching the wood and prevent combustion from occurring, although the drop tests (particularly the punch test) prior to the thermal test may have damaged the cladding and exposed the wood. A practical test, on either an actual package or suitable test section, will therefore almost always be required to demonstrate that any wood near the surface of a package or shock absorber will not burn or, if it does burn, to determine the heat that is released. It should be noted that some woods, such as cork, char when heated but generally produce insufficient heat to sustain burning when removed from the external source of heat.



FE model of Safkeg 2816G with impact damage

The Application of Boundary Conditions

Many designs of transport package involve different components nested one inside another. Clearances will be included so that the package can be assembled. These clearances will result in narrow air gaps existing between structures which can present significant thermal resistances. If an air gap is narrow, convective heat transfer will be negligible and the heat transfer will be dominated by thermal radiation and conduction. Some gaps may have a precisely engineered width. Most, however, will be uncertain to some extent. The analyst will need to consider what range of gap width is possible and whether the assumption of a large or small gap will be pessimistic.

ANALYSIS – NORMAL CONDITIONS OF TRANSPORT

Validation of Models

Prior to using an FEA or CFD model to predict the temperature of a package under normal conditions of transport, the model should first be validated against any normal operation thermal tests which have been performed. Parameters which are uncertain such as gap widths, the thermal conductivity of natural materials (such as cork) and the contact resistance between touching components can be varied in order to improve the agreement between measured and predicted temperatures but such parameters should not be extended beyond what might reasonably be expected to occur. The boundary conditions applied to the exterior of the model should reflect the measured ambient temperature in the test.

Adjustment of Model to the Test Conditions

The model should then be modified to reflect the conditions specified in the IAEA Regulations. At least two calculations will be required, one representing steady conditions with no solar insolation, the other with solar insolation. The first of these is a steady-state calculation while the second may require a transient calculation.

The heat generated by the radioactive material inside the package will need to be represented in the model. This may be done by explicitly representing the radioactive material with a volumetric heat generation rate. Alternatively the heat may simply be input as a heat flux on the inner surface of the package. The analyst will need to ensure that the distribution of this heat flux corresponds to what would be expected under the transport conditions being considered. For example, if heat transfer between the radioactive material and the package inner surface is dominated by natural convection, the heat flux to the region of the package surface below the bottom of the radioactive material will be much less than that to the package surface above it.

Modelling Solar Insolation

The IAEA Regulations specify the solar insolation flux which should be assumed, for 12 hours each day, onto different shapes and orientations of surface. However, some degree of judgement and common sense needs to be applied when deciding the solar insolation flux to apply to different surfaces. It is recommended that a ‘broad brush’ approach be used so that different fluxes are not applied to each side of small features (such as handles or lugs) but instead a uniform flux is applied to all surfaces on one side. Similarly, a degree of compromise should be allowed when judging which category a particular surface fits into, for example, when considering whether a downward facing surface is a ‘flat surface transported horizontally’ or ‘other downward facing surface’.

The application of solar insolation can be problematic for complex geometries such as a finned surface. It would obviously be unreasonable to fully apply the insolation flux to both sides of the fins plus the base of the fin cavity. The solar insolation data given in the IAEA Regulations are intended to simulate the heat flux onto the outer envelope of the package. For a complex surface geometry (such as a finned surface) one method of representing this is by adjusting the temperature to which the surface of the package is exchanging heat by radiation. For example, for a black body, a radiation heat flux of 800 W/m^2 can be represented by changing the surface temperature to T_{eff}, given by the equation:

$$800 = \sigma \left((T_{eff} + 273.15)^4 - (38 + 273.15)^4 \right)$$

where σ is Stefan's constant and T_{eff} is in °C.

It should be noted that the IAEA Regulations specify the solar insolation heat fluxes incident upon the surface of the package. The heat flux which is absorbed by the surface is this heat flux multiplied by the absorptivity of the surface but the absorptivity at the short wavelengths typical of solar insolation will not necessarily be the same as the emissivity at the longer wavelengths typical of heat loss from the package surface. Reliable data on absorptivity at short wavelengths may not be available for many materials and pessimistic assumptions may have to be made by the analyst or appropriate measurements made.

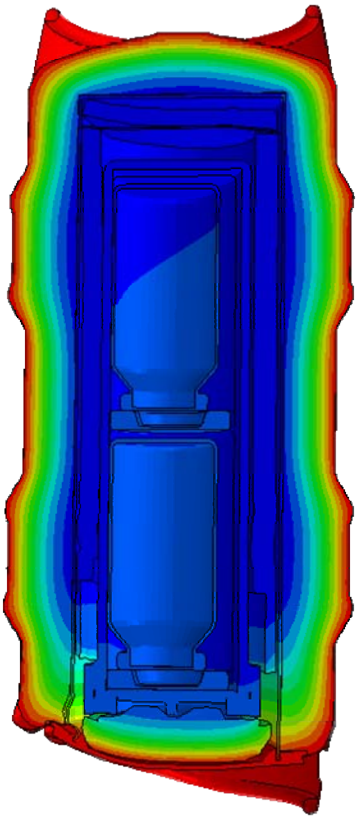
ANALYSIS – FIRE ACCIDENT CONDITIONS

Validation of Model for Fire Accident Conditions

The model used to model the fire accident is usually very similar to that used to model normal conditions of transport. Some modification of the model will probably be required, however, to represent the damage caused to the package by the impact tests. If a practical fire test has been performed on the package, this should first be modelled in order to validate the model.

When modelling a practical test that has been performed, the boundary conditions and length of test should be based upon the measured conditions in the fire or furnace. If necessary, parameters such as the conductivity of natural materials (such as cork) or the size of gaps (following being subjected to the drop tests) can be adjusted to ensure that the model is not over-optimistic compared to the measured test data.

Some materials used in transport packages are combustible and may continue to burn, generating heat, long after the 30 minute (60 minute for Type C package) heating phase of the thermal test has finished. If such burning is possible, particularly in a drop-test damaged package, then the analyst will need either to demonstrate why continued burning will not occur or make allowance for it in the thermal model.



Temperature at end of fire predicted using FE model of Safkeg 2816G

Establishing Boundary Conditions

The IAEA Regulations require that the starting point for the thermal test is the temperature profile under normal conditions of transport. The effect of solar insolation needs to be included so the temperature profile at the end of the 12 hour 'day' should be used. It is worthy of note that Paragraph 667 of the current IAEA Regulations, which give the requirements for a Type B(M) package, do not include Paragraph 728 (the specification of the thermal test) in the list of Paragraphs for which revised conditions may be specified by the competent authority. This could be interpreted to mean that, for a Type B(M) package, even if an ambient lower than 38°C is used to assess normal conditions of transport, the conditions at the start of the thermal test should still correspond to the 38°C ambient temperature. An ambient of 38°C would also have to be assumed during the cooling phase of the thermal test.

Absorption of Heat by the Package

The IAEA Regulations specify the flame temperature, the emissivity of the flames and the absorptivity of the package surface which should be assumed if no other value can be justified. In practice it would be hard to justify the emissivity of a surface when the surface may be oxidized by the high temperatures or blackened by soot from the fire. It is therefore recommended that the value of 0.8 specified in the IAEA Regulations is used. The emissivity of 0.9 specified for the flames introduces some degree of uncertainty when included in a thermal model since the view factors at any surface must sum to unity. The easiest way to avoid having to justify the way in which the emissivity of the flames have been modelled is to pessimistically model the flame emissivity as being unity (i.e. the flames are a black body).

If the package is finned the Advisory Material (IAEA, 2008), allows the emission of radiation from the flames within the fin cavities to be ignored and modelled as from a surface outside the fins. The modelling of the radiation heat transfer inside the fin cavities should include the effects of reflection of radiation and radiation from the hot fin tips to the cooler base of the fin cavity.

The Cooling Phase

According to the IAEA Regulations, the boundary conditions on the exterior of the package during the cooling phase of the thermal test should be the same as those applied when modelling normal conditions of transport. With regard to solar insolation, if the temperature profile at the start of the fire corresponded to the end of the 12 hour ‘day’ during which solar insolation was incident upon the package, then logically the first 11½ hours of the cool-down period will occur during the ‘night’. However, the analyst would need to demonstrate that this was a more pessimistic assumption than starting the fire at the beginning, or part way through, the ‘day’ and the package receiving solar insolation at the start of the cooling period. Rather than perform several fire test transient calculations, with the fire starting at different assumed times, a simpler and clearly pessimistic approach is to assume that the fire starts at the end of the 12 hour insolation period and that a further 12 hour insolation period starts at the beginning of the cool-down phase.

If the boundary conditions during the cool-down phase of the thermal test were identical to those during normal transport, the emissivity of the surface of the package would correspond to that of the paint or metal of the outer surface, which may be significantly different from the value of 0.8 assumed during the heating phase of the fire. If the normal emissivity of the surface is greater than 0.8, it is unreasonable to assume that the emissivity of the surface suddenly increases at the end of the fire. However, if the normal emissivity of the surface is less than 0.8, it is reasonable to assume that the emissivity of the surface remains at 0.8 during the cool-down phase of the fire transient.

BEST ESTIMATE OR PESSIMISTIC?

The objective of performing a CFD or FEA thermal analysis is to demonstrate that the package design satisfies the requirements of the IAEA Regulations. There are no confidence limits specified in the Regulations, hence the designer must demonstrate that the safety performance of the package meets or exceeds the regulatory requirements.

There are a number of parameters that will influence the thermal performance including:

- The material properties
- The size of air gaps
- The emissivity of surfaces
- The time of the start of the fire test relative to the solar insolation period
- The behaviour of materials that might char, shrink or burn during the fire test
- The contact resistance between components.

While it would be possible to use the best estimate for each of these parameters, it would then be necessary to perform sensitivity calculations to determine the significance of the uncertainty in each parameter upon the predicted temperature at the locations of interest, and to use reasoned argument to justify the combined effect of the uncertainties. An easier approach is to select reasonably pessimistic values for each of the assumed parameters so that sensitivity calculations are not then required.

When validating a thermal model against data from thermal tests, parameters should be adjusted, within the bounds of what is reasonable, so that the model is always pessimistic. For some parameters it may not be self evident whether a high or low value will be pessimistic. For example, if cork is used as insulation in a package design, a high value of thermal conductivity will increase the heat entering the package during a fire test but a low value of thermal conductivity will increase the temperature of the package under normal conditions of transport and during the cooling phase of the fire test. One approach to resolving this problem is to perform a number of fire test calculations with different assumed values of thermal conductivity. Alternatively, the self evident pessimistic value could be used in each phase of the calculation.

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